International Journal of Power Electronics and Drive System (IJPEDS)
Vol. 10, No. 4, December 2019, pp. 1806~1814
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v10.i4.1806-1814 ❒ 1806

High performance DC/DC buck converter using sliding mode controller

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Article Info

Article history:

Received Mar 31, 2019
Revised Apr 20, 2019
Accepted Jul 22, 2019

Keywords:

DC/DC converter
Non-linear control system
Sliding mode control

ABSTRACT

This paper investigated the performance of the sliding mode control technique for DC/DC converter using frequency response method. The applications of the step down type switching regulator) buck converter (are found in the devices that use batteries as power source like laptop, cell phones, electric vehicle, and recently, it has also been used in the renewable energy processing, as a maximum output power can be achieved at higher efficiency. In order to optimize the efficiency and for convenient power management, the issues like power on transients, the effect of load variation, Switching and Electromagnetic interference (EMI) losses has to be overcome for which controllers are used. In the proposed method, pulse width modulation (PWM) based on proportional-integral-derivative sliding mode voltage controller (PID SMVC) is designed for a buck converter and the response for appropriate control parameters has been obtained. The system stability has been examined and analyzed from the performance characteristics, which shows clearly that the buck converter controlled by the sliding mode controller has fast dynamic response and it's very efficient for various applications.

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1. INTRODUCTION

The sliding mode controller (SMC) is a non-linear control method that changes the dynamics of a non-linear system which forces the system to slide. The SMC well known by its robustness, high stability and simple implementation [1-5]. One application of SMC is the control of electric drives operated by switching power converters. The DC/DC converters must work with suitable control technique in order to cope with their intrinsic nonlinearity, sudden load changes, wide range of input voltage, and to guarantee stability at any operating condition while providing quick transient response [6-8]. The SMC technique can be a possible option to control these type of circuits, since the switching converters model a case of variable construction systems [9].

The literature review shows that the authors suggest various methods to design SMC controller. In [10] the author designed and analyzed a robust SMC for the control of DC/DC buck converter, a buck converter with two loop control is employed. The system controlled using SMC is tested and gives robustness under input voltage variations and step load changes. The theoretical prediction results are validated by means of simulations using program Matlab. In [11] the author uses a fixed frequency PWM based on SMC for DC/DC converters operating in the continuous conduction mode (CCM). A prototype for the system is developed and the experimental results validate the design methodology. In this paper a frequency response method is used to investigate the SMC used to control DC/DC buck converter, and the

performance of the controller is assess by using the graphs presented by the polar plot, root locus, Nyquist plot and bode plot, which obtained by using the Matlab program. The organization of the paper is as follows: section 1 the introduction.

Section 2 describes the mathematical and state space modeling of DC/DC buck converter, which is followed by section 3 that shows the design of the SMC for the DC/DC buck converter. Section 4 shows the system modeling. Section 5 the simulation and experimental results are presented. Conclusions are reported in section 5.

2. MATHEMATICAL AND STATE SPACE MODELING OF BUCK CONVERTER

The topology shown in Figure below, is used in order to get the differential equations that describes the DC/DC buck converter, the circuit consists of switch (IGBT), output filter, diode and output load presented by resistive load (r_L), the direct application of the Kirchhoff's current and voltage laws are used to procure the equations that describe the dynamics of the converter for each possible circuit topology (differential equations), the topologies are shown from the particular assumed switch position function value (u) [12].

Thus, as shown in Figure 1(b), when the switch position exhibit at u=1 (T_{ON}), the topology congruous to the non-conducting mode for the diode gained and current will flow to the load and the inductance L will start to store magnetic energy. Alternatively, as shown in Figure 1(c), when switch position is at u=0 (T_{OFF}), the input voltage source will be disconnected and the inductor will behave as a source and passes the stored energy in it to the load [13].

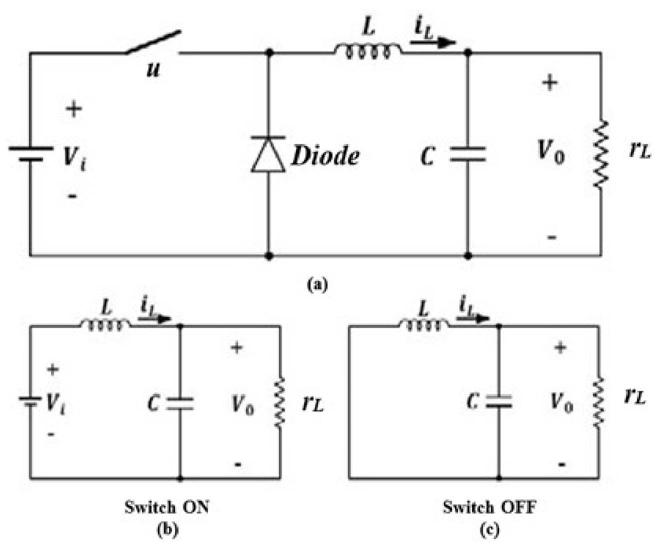

Figure 1. (a) Buck converter circuit structure; (b) converter equivalent circuit during u=1 (T_{ON}); (c) converter equivalent circuit during u=0 (T_{OFF})

The circuit digram shown in upper figure can mathematically represented by the following group of equations [14]:

$$L\frac{di_L}{dt} = uV_i - V \tag{1}$$

$$C\frac{dv_O}{dt} = i_L - i \tag{2}$$

Where L and C is the inductance and the capacitance of the output filter, i_L is the current passes through the inductor, V_o is the output voltage (i.e. same as capacitor voltage), V_i is the input voltage provided

from external voltage source (DC voltage source), and u is the switch position and presents (ON-OFF) that controlled the input signal by taking discrete values of 1 (switch is ON) and 0 (switch is OFF) [15].

$$i_o = \frac{V_o}{r_L} \tag{3}$$

By substituting equation (3) in equation (2) and rewrite equations (1), (2) in the state equations form by take i_L and Vo as the system states, the next state equations are given:

$$\frac{di_L}{dt} = \frac{V_i}{L}u - \frac{V_o}{L} \tag{4}$$

$$\frac{dV_o}{dt} = \frac{i_L}{C} - \frac{V_o}{r_L C} \tag{5}$$

By using the state equations (4) and (5), buck converter block diagram can be build as shown in Figure 2.

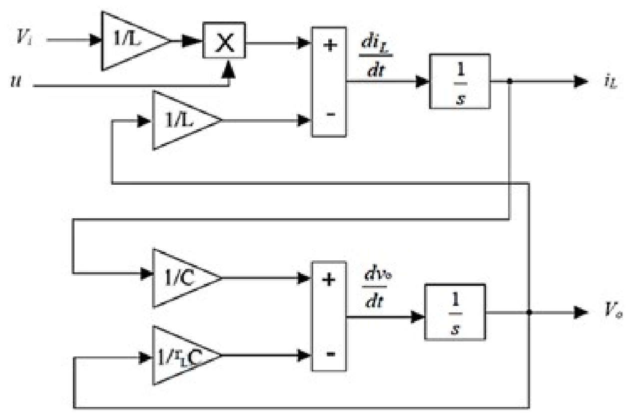

Figure 2. Buck converter block diagram using the state equation [11]

3. SLIDING MODE CONTROL (SMC)

Hence, the SMC controller is design in two parts, the first part contain the design of a sliding surface in order to make the sliding motion to be content with the design features. The second part is the part that deals with the chosen of a control rule makes the switching surface engaging to state of the system. The working principle of SMC is to impose the state of the system to be stable for any values of initial condition by driving the states of the system upon a special surface in the state space, which known as the sliding surface i.e. for any disturbances in the system for any reason, the states of the system is coercive to go back to line (S=0) and holding the sliding mode function (S) to zero. At the time that the sliding surface is attained, the controller retain the states on the close proximity of the sliding surface, the sliding surface is described by (S=0) [16].

For infinite rapid switching state, the system will make movement over the line after several restricted time, this movement known as sliding mode and this presented the ideal motion of the system. The system state is ON & OFF state of switch of the buck converter. Figure 3 shows the block diagram of SMC controlled buck converter. If the switch is in ON condition, the sliding function will be greater than zero (S > 0) and the switch is in OFF condition (S < 0) [17, 18]. The sliding modes can be theoretically described by the system stays closed to the sliding surface and need only be viewed as sliding along the surface. In sliding control mode, there are two modes the reaching mode and the existing mode. During the beginning (initial phase) the system cannot goes to the switching surface (i.e. at S=0), because of that a control aimed across the sliding surface is known as the reaching mode. After that the system gaining the reaching mode it must be

stable in that condition (S=0) this named as the existing mode, this mode is called sliding mode [18]. Figure 4 shows the two modes of variable construction control system.

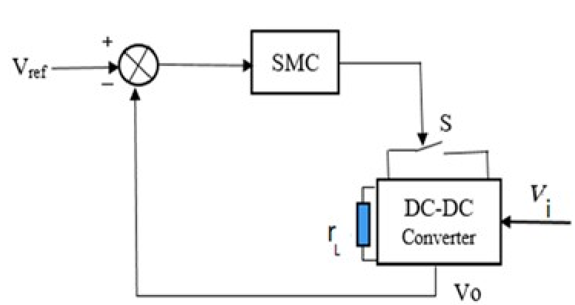

Figure 3. Block scheme of buck converter

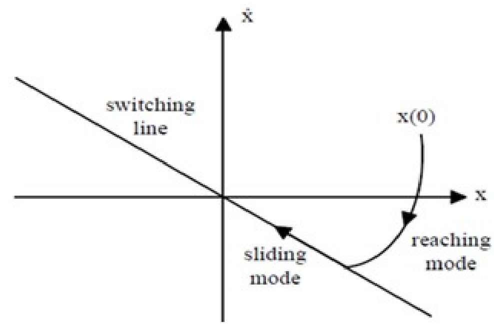

Figure 4. The modes of SMC system controlled by SMC [10].

As an example Figure 4 display the trajectory of a system under SMC. After the initial reaching phase, the system states "slides" along the line (S=0). The certain (S=0) surface is chosen due to his capability to minimize order dynamics when compeled to it. In this situation, $S=x_1+\dot{x}_1$ will be equal to zero, the surface that matches to the first order system $\dot{x}_1=(-x_1)$, which has an exponentially stable origin.

4. SYSTEM MODELLING

Figure 5 shows the schematic diagram of the PWM based PID SMVC converters, as mentioned before a mathematical model of the buck converter is derived in previous section of this paper using the laws of circuit analysis. The buck converter is loaded with resistive load (r_L), and the output voltage (V_o) of the converter controlled by SMC. Assumed that the converter to be operated in CCM. For the case of PWM based on PID SMVC converters, the control variable x can be presented in the form:

$$x_1 = V_{ref} - \beta V_O \tag{6}$$

$$x_2 = \dot{x}_1 = \frac{\beta V_o}{r_L C} + \int \frac{\beta(V_o - V_i u)}{LC} dt \tag{7}$$

$$x_3 = \int x_1 dt = \int (V_{ref} - \beta V_o) dt \tag{8}$$

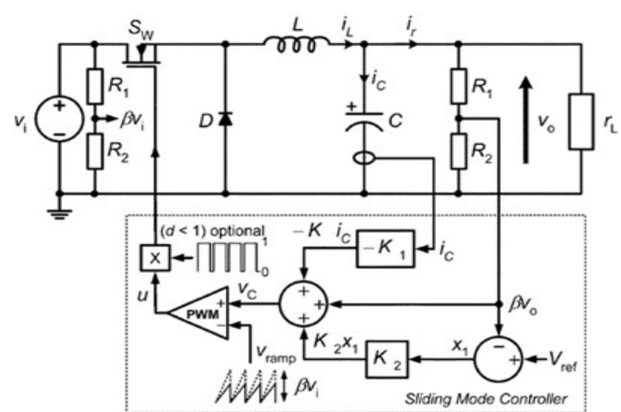

Figure 5. Complete schematic diagram of the SMVC converters [10]

Where the variables x_1, x_2 and x_3 represent the voltage error, the rate of change of the voltage error, and the integral of voltage error [19]. Where $\beta=R_2/(R_1+R_2)$, is the voltage divider ratio [11]. The design of the buck converter controller needs state space descriptions, which as follow [20]:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & \dfrac{-1}{r_L C} & 0 \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} 0 \\ \dfrac{-\beta V_i}{LC} \\ 0 \end{bmatrix} u + \begin{bmatrix} 0 \\ \dfrac{\beta V_o}{LC} \\ 0 \end{bmatrix} \tag{9}$$

After having the state space characterization, now the following stage is the controller design. For this system, it's suitable to have a universal SMC control rule that embrace a switching function (S) such as u=0 (when S<0) and u=1(when S>0), Where S is the immediate state variable's route, and can be written as:

$$S = \alpha_1 x_1 + \alpha_2 x_2 + \alpha_3 x_3 = J^T x \tag{10}$$

$$J^T = [\alpha_1 \quad \alpha_2 \quad \alpha_3] \tag{11}$$

Where α_1, α_2 and α_3 representing the control parameters termed as sliding coefficients. However, when the system reaches the steady state, actually it becomes a fixed point, that's leads to removing the integral control. The control signal (v_C) then reduced to PWM PD linear controller form, and the formula became:

$$v_c = -K_1 i_c + K_2 (V_{ref} - \beta V_o) + \beta \tag{12}$$

Where K_1 and K_2 can be found from:

$$K_1 = \beta L \left(\frac{\alpha_1}{\alpha_2} - \frac{1}{r_L C} \right) \tag{13}$$

$$K_2 = LC \left(\frac{\alpha_3}{\alpha_2} \right) \tag{14}$$

K_1, K_2 are the gain constant for the feedback signals, and their values can be determined in the terms of converter component L, C and r_L and values of sliding parameters α_1, α_2, and α_3. The sliding coefficients can be found by putting S=0, and compare this equation with standard second order system form [21, 22]:

$$\alpha_1 x_1 + \alpha_2 \frac{dx_2}{dt} + \alpha_3 \int x_1 = 0 \tag{15}$$

$$\alpha_1 x_1 + \alpha_2 \frac{dx_2}{dt} + \alpha_3 \int x_1 = 0 \tag{16}$$

Where: $w_n = \sqrt{\dfrac{\alpha_3}{\alpha_2}}$, is the undamped natural frequency, $\varepsilon = \dfrac{\alpha_1}{2\sqrt{\alpha_2 \alpha_3}}$, is the damping ratio,

$f_{Bw} = \dfrac{w_n}{2\pi} \sqrt{\dfrac{\alpha_3}{\alpha_2}}$, is the controller's response bandwidth.

$$\frac{\alpha_1}{\alpha_2} = 4\pi f_{Bw}, \text{ and } \frac{\alpha_3}{\alpha_2} = 4\pi^2 f_{Bw}{}^2$$

Using f_{Bw}=2 KHz, consequently the design of the sliding coefficient is now count on on the bandwidth of the required frequency response on coupling with the stability provision [23]. Now by substituting the value of f_{Bw} we get:

$$\frac{\alpha_1}{\alpha_2} = 4\pi(2*10^3) = 25120 \text{ and } \frac{\alpha_3}{\alpha_2} = 4\pi^2\,(2*10^3)^2 = 157753600$$

The reference voltage is set as V_{ref} =5V, and V_o =24V corresponding to V_{in}=48V which gives:

$$\beta = \frac{V_{ref}}{V_o} = 0.2083334$$

The state of the converter in which the i_L never reaches zero for any period of time is called the CCM. Therefore the filter L and C takes approximately the following values:

$$L_{(\min.)} = \frac{(1-D)r_L}{2f} \tag{17}$$

$$C_{(\min.)} = \frac{(1-D)V_o}{8V_r L f^2} \tag{18}$$

Where D is the duty cycle and equal to D = 0.5, r_L = 10Ω (maximum load resistance), f =20 kHz, (V_r/V_o)=1%. The boundary ($L_{(\min.)}$ = 125µH). For ($L > L_{(\min.)}$), the converter operates in the (CCM). A value of (140µH) is chosen, the current passing in the inductor filter (i_L) is in the CCM and having two components the first is DC component (I_o) with an ac component flows through the filter capacitor C as capacitor current I_c compose of a triangular, this current is the reason of the ripple appears in the output voltage from the converter. To reduce the peak-to-peak ripple value below a certain value (V_r), the capacitor of filter should be more than the minimum capacitance is equal to (125µF). In this paper a value of (250µF) is chosen [24].
According to the above values, the implemented control signal (v_C) equation is:

$$v_c = \text{-}0.6433 i_c + 4.9298(V_{ref} - \beta V_o) + \beta V$$

5. SIMULATION RESULTS AND DISCUSSION

The following steps illustrated the simulation procedure that executed using the software (Matlab/Simulink 2016-b) programmable and the discussion for the results is shown, Table 1 shows the values of the components and parameters of buck converter based on SMC controller. Figure 6 shows the Matlab/Simulink program for the modeling of DC/DC buck converter based on SMC; the program structure consists of the equation on each of three possible operating stages. The default values of converter parameters; the input voltage (V_{in}), the inductance value, the capacitor value, and the load value r_L.

Table 2 shows the output voltage (V_o) and output current (I_o) results of the *DC*/*DC* buck converter for different values of output load (r_L), which conformed that the system under SMC not or less affected by the changing on the output load resistance. Figure 7 and 8 shows the PWM signal at the gate of the IGBT switch and the current pass through the capacitor I_c when the system controlled by SMC.

Table 1. Specifications of the proposed system

Parameter	Description	Nominal Value
V_{in}	Input voltage	48 V
V_o	Desired output voltage	12 V
f	Switching Frequency for Buck Converter	20 kHz
L	Inductance	140 µH
C	Capacitance	250 µF
r_{Lmin}	Minimum load resistance	1Ω
r_{Lmax}	Maximum load resistance	10 Ω

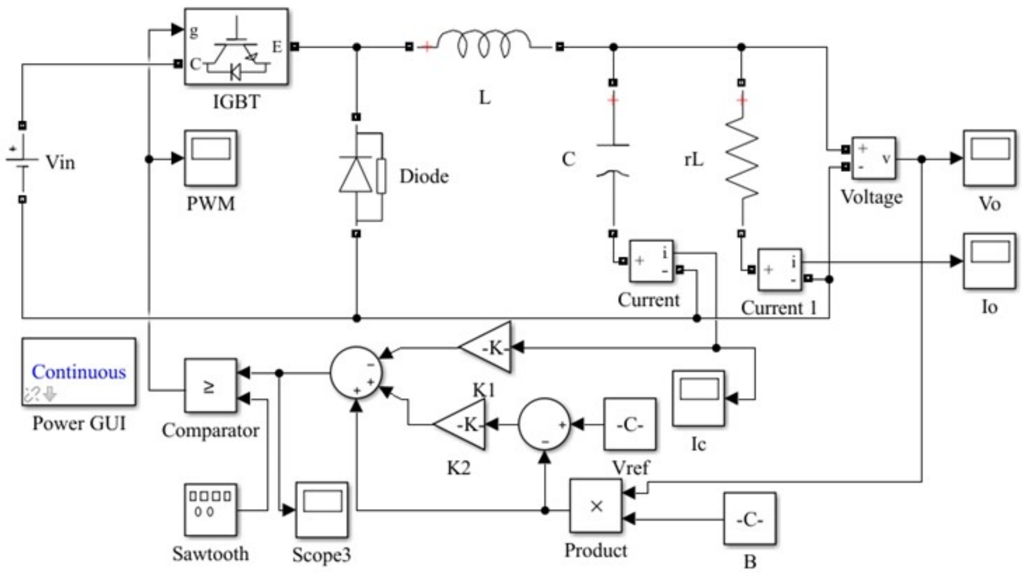

Figure 6. Modeling of DC/DC buck converter based on SMC using matlab /simulink

Table 2. Simulation results of the system

r_L (Ohm)	V_o (Volt)	I_o (Amper)
1	22.96	22.97
2	23.59	11.86
3	23.61	6.947
4	23.61	5.122
5	23.61	4.64
6	23.61	3.956
7	23.61	3.39
8	23.61	2.967
9	23.58	2.629
10	23.46	2.44

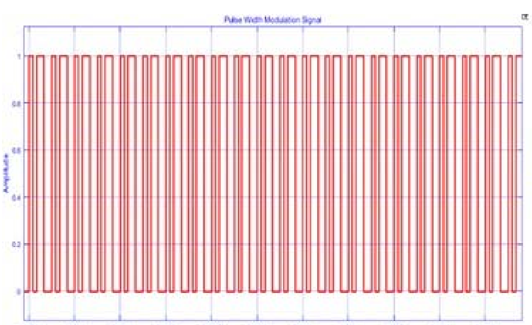

Figure 7. IGBT gate signal of the DC/DC buck converter

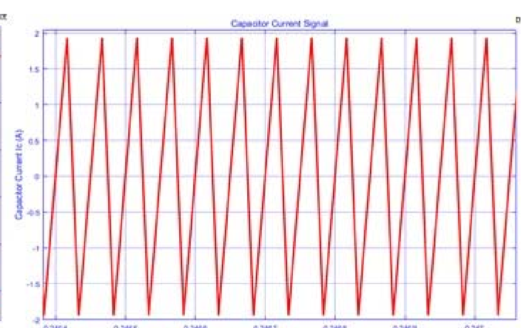

Figure 8. Capacitor current signal I_c

Figures 9 and 10 shows the output voltage signal V_o and current I_o for the buck converter system controlled by SMC with input voltage V_{in}=48V and r_L= 6 Ω of output load resistance (resistive load), which gives output voltage V_o= 23.61 V (with very low voltage ripple) and output current I_o= 3.95 A.

The system step response under SMC control is shown in Figure 11. The controller in this system eliminated overshoot, steady state error and decreasing the settling time (i.e. the system reach to the stability faster with settling time equal to (0.984 Sec). Figure 12 shows the Nyquist diagram of the proposed system with SMC controller. As shown in the figure, the point (-1+0j) outside the region enclosed by the Nyquist

plot, which indicates that the system is stable. Figure 13 shows the root locus of the system with controller. No poles or zeros of the system lies on right-half of S-plane, also the behavior of the Roots Locus indicates that the system is stable. Figure 14 shows the bode-plot of the system with SMC controller the phase and magnitude graphs indicates that the system is stable.

Figure 9. Buck converter output voltage V_o

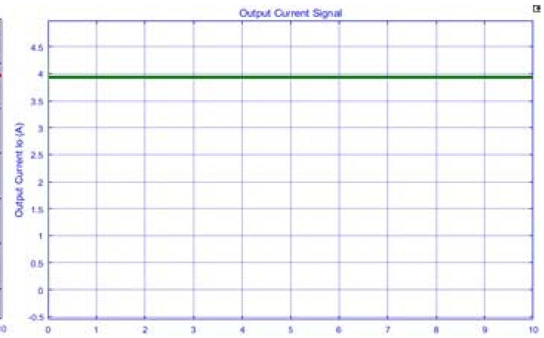

Figure 10. Buck converter output current I_o

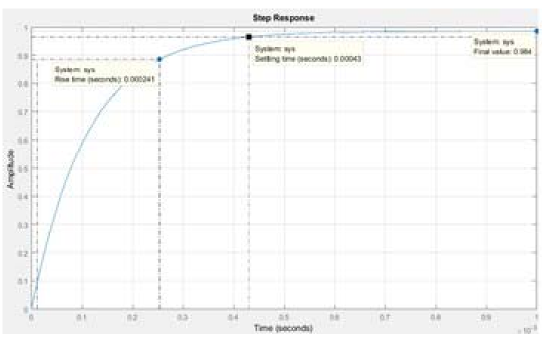

Figure 11. Step response of the system with the SMC

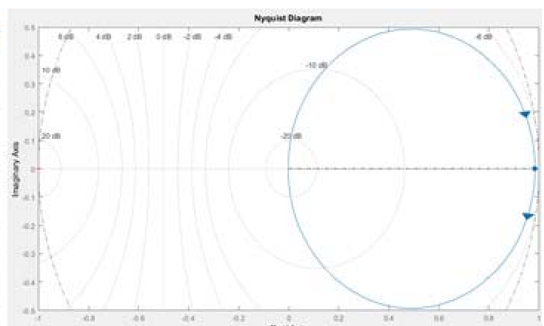

Figure 12. Nyquist diagram of the system with SMC

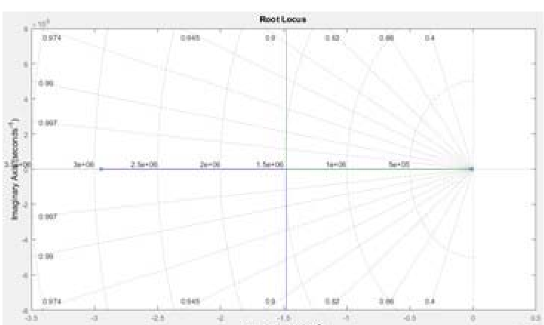

Figure 13. Root locus of the system with SMC

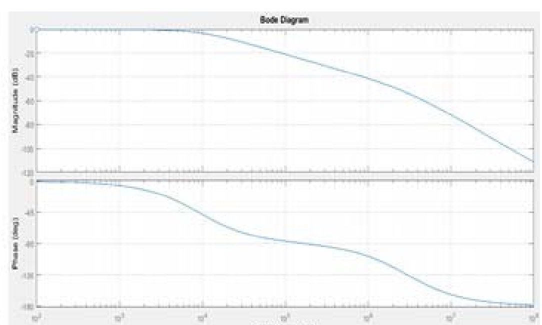

Figure 14. The bode plot of the system with SMC

6. CONCLUSIONS

The present work investigated the performance of SMC controller for DC/DC buck converter by tuning the values of the gain vector K as shown in table 1. Regarding the simulation results obtained from the system of buck converter (table 2) confirmed that the SMC controller is a robust controller against load changes and it strongly less sensitive to disturbances like power supply variations. Smooth output voltage response observed with zero error steady state and goes to stability faster. The step response, root locus, nyquist diagram and bode plot figures confirmed the stability of the system.

ACKNOWLEDGMENT

The authors would like to thank the Iraqi government represented by the ministry of higher education and scientific research, Mustansiriyah University (www.uomustansiriyah.edu.iq) Baghdad – Iraq for its support in the present work.

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